

# Bunch shaping experiments at the High Brightness Electron Beam Source Laboratory (HBESL)

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**Abstract.** In this paper, we present recent results from bunch-shaping experiments using  $\alpha$ -BBO crystal at the High Brightness Electron Beam Source Laboratory (HBESL).  $\alpha$ -BBO crystals were used to shape the ultra-short laser pulse ( $<100$ fs) at HBESL to generate twin pulses at the cathode. The twin electron pulses were transported down the linac ( $< 5$  MeV) to a transverse deflecting mode cavity and the temporal profile recorded on the screen. The longitudinal time profile of the twin pulses show the difference between the effect of crystals and the longitudinal space charge effect. The electron beam was recorded for various position of the crystal and bunch charge.

**Keywords:** drive laser shaping, longitudinal space charge, photoinjector, bunching, deflecting mode cavity

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## INTRODUCTION

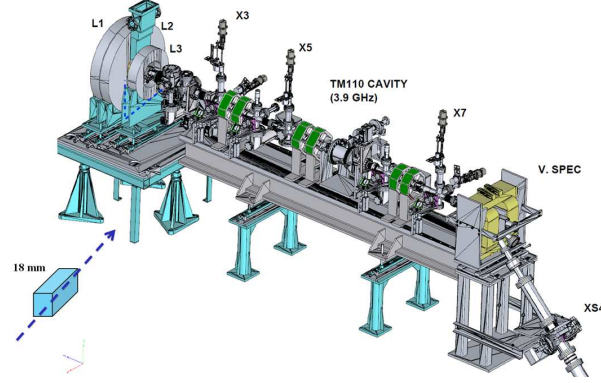
There are always fluctuations in the beam density and beam energy on laboratory particle beams even under the best of conditions. Thus, efforts to model and understand these fluctuations have long been a focus of intense beam research. Recent experiments have shown that a high brightness beam along a linac can also be a source of modulations both in energy (introduced primarily by longitudinal space charge impedance) and in density (generated by compression using dispersive elements)[1]. Electron bunches can be shaped in various ways. To have precise control over the longitudinal bunch profile, shaping is often performed by shaping the photocathode drive laser. Ultra-short (fs - ps) laser shaping is a separate field of R&D and a wide variety of techniques are possible. Typically, such techniques are done in the IR and are at kHz repetition rate[2]. For modern accelerators based on superconducting technology, UV pulse shaping based on  $\alpha$ -BBO crystal is a cheap, compact, power-efficient technique that is also scalable to MHz repetition rates[3, 4]. In this paper, we present results from bunch shaping experiments at HBESL using  $\alpha$ -BBO crystals.

## HBESL

HBESL is an electron source R&D facility that consists of a normal conducting L-band (1.3 GHz) RF photoinjector powered by a 3 MW klystron. The beam after exiting the gun is focussed by solenoids and then transported via a quadrupole lattice to a deflecting mode cavity which is followed by a vertical spectrometer and beam dump. The deflecting mode cavity is a normal conducting, water cooled, 3.9 GHz copper cavity that is powered by a 50 kW klystron. While our experiment used a UV laser ( $\sim 100$ fs) illuminating a Cs<sub>2</sub>Te photocathode, several experiments involving multiphoton emission[5], ellipsoidal bunch generation[6], diamond field emitter array cathode[7], carbon nanotube cathodes, channelling radiation[8] and inverse Compton scattering[9] have been done or proposed at HBESL. The  $\alpha$ -BBO crystal is placed right before the UV enters the cathode and the amount of UV sent to the crystal is controlled using a remote-controllable aperture. The crystal rotation angle is set manually. An alignment laser is used to ensure proper alignment with and without the crystal in place.

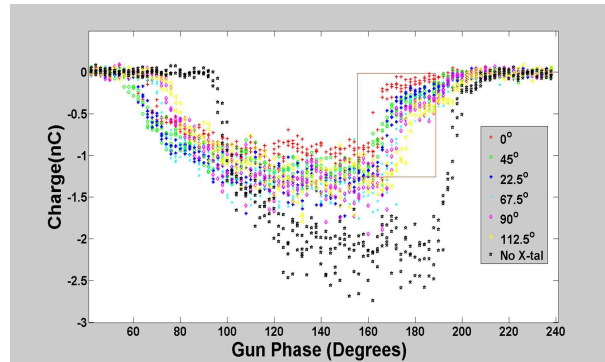
## THEORY OF PULSE SHAPING

Materials that exhibit anisotropy in the refractive indices for two different polarizations of the incident light are called birefringent crystals. In such crystals, a temporal separation between the ordinary ray (perpendicular to the optical axis)



**FIGURE 1.** Schematic of the HBESL facility showing the crystal placed just before the UV hits the cathode.

and the extraordinary ray (parallel to the optical axis) occurs as the light travels through the crystal. The separation is proportional to the group velocity mismatch due to the two different indices of refraction. A very important point to note is that the group index of refraction  $n_g = n - \lambda \frac{dn}{d\lambda}$  should be used in this calculation. Therefore, the time separation between the pulses after passing through a crystal of length  $L$  can be written as  $\delta t = L \frac{\delta n_g}{c}$ . In practical units,  $\frac{\delta t}{L}$  is equivalent to delay per unit length of the crystal. For an  $\alpha$ -BBO crystal at  $\lambda = 263$  nm, the theory along with appropriate Sellmeier equation predicts a delay of 0.864 ps/mm. Therefore, the distance between the two outgoing pulses is fixed by the length of the crystal which is not a free parameter during our experiment. The pulse length of the individual pulse remains unaffected as the group velocity dispersion along the polarization direction is small. The flexibility of this technique stems from the fact that by rotating the crystal on the plane perpendicular to the direction of propagation, the amplitude of each of these pulses can be changed. For example when the incident light is  $45^\circ$  to the optical axis, two pulses of equal intensity are generated, whereas only one pulse is generated when the incident light travels directly along the axis. By adding multiple crystals, one can generate a pulse train, each pulse separated in time with variable amplitude. Many experiments have demonstrated this technique[10]. The number of crystals used in the experiment is limited practically by the laser energy and transmission efficiency. Ultimately at some point, the length of the pulse becomes large compared to RF-wavelength for ps-lasers and mm-sized crystals. It is worth pointing out that instead of crystal length, thermal effects can be used to change the birefringence of the crystal[11]. Alternatively, one way of achieving finer control over the length of the crystal would be to use a wedge shaped crystal as in a Soleil compensator. But practical implementation of a wedge might be limited only to translation motion which will still introduce a transverse offset to the laser path. Rotating a wedge will be more challenging since it requires re-alignment of the laser to the cathode for every position.



**FIGURE 2.** Gun phase scan with an  $\alpha$ -BBO crystal at different angles. The black curve is the phase-scan without any crystal. The boxed portion indicates the presence of an extra shoulder in the curve.

**TABLE 1.** Rotation angle vs Peak intensity vs phase separation

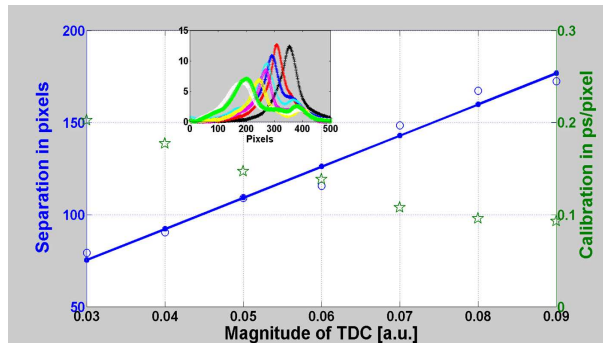
Angle	Ratio $\frac{I_1}{I_2}$	$\Delta\phi$
45°	2.4	8.6°
67.5 °	3.8	7.4°
90 °	4.1	8.2°
112.5°	2.6	7.8°

## EXPERIMENTAL RESULTS

Our experimental setup had one crystal of length 18 mm. The crystal used was 5 mm x 5 mm transversely. The crystal was mounted in a marked rotatable mount that could be completely removed to use as a control variable. Before and after installing the crystal, a gun phase scan in step of 2 ° with 4 samples at each point was taken. The measurement was repeated for several crystal angles.

### Experimental results with one crystal

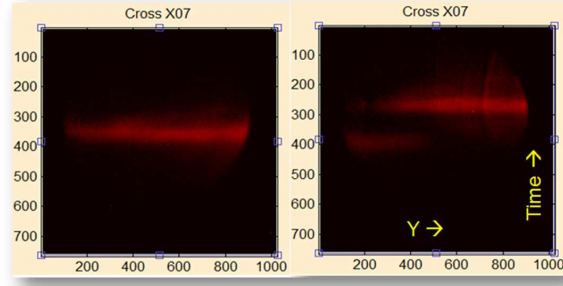
Most manufacturers of  $\alpha$ -BBO crystals provide a birefringence, it is typically not with the group velocity dispersion. So, it is better to actually measure the birefringence of the crystal in the laboratory. Separate experiments were done at the Advanced Superconducting Test Accelerator (ASTA) laser lab to measure the birefringence of the crystal[12]. The gun phase scans for several angles between the optical axis of the crystal (OA) and the incoming laser polarization (LP) are shown in Fig. 2. The gun phase scan with the crystal indicated a shoulder during the falling side of the phase and as expected showed a delay due to the presence of the crystal (black curve Vs all other curves). Notice also that the maximum charge extracted with the crystal drops about a factor of two due to pulse-splitting and transmission loss through the crystal. Depending on the crystal angle, the position of the shoulder changes. In order to extract the distance between the two peaks we did the following procedure: (a) Assign  $f(\Phi)$  as a function to the phase scan curve obtained for the crystal with zero angle between the OA and the LP, when no pulse-splitting is observed. (b) For all other phase scans with different angles fit the experimental scans with the equation:  $I_1 f(\Phi + \phi_1) + I_2 f(\Phi + \phi_2)$  where  $I_1, \phi_1, I_2, \phi_2$  are fitting parameters (c) Extract the  $\frac{I_1}{I_2}$  and  $\Delta\phi = \phi_1 - \phi_2$ . The  $\Delta\phi$  in ps [for 1.3 GHz,  $360^\circ \sim 776$  ps] is the separation between the twin pulses. The results are listed in Table 1. The distance between the two pulses remains more or less a constant at  $16.8 \pm 1$  ps and agrees well with the theoretical prediction of 15.58 ps.



**FIGURE 3.** The separation of the twin pulses as a function of the deflecting cavity strength. The y-axis on the right is the calibration based on the fixed distance between the pulses. The inset shows the vertical projection taken from the images of the X7 screen.

### Experimental results with deflecting mode cavity

The twin pulse was transported downstream of the gun and the longitudinal time profile of the twin pulse was recorded as a function of the deflecting cavity strength. Because the beam energy is less than 5 MeV, the requirement

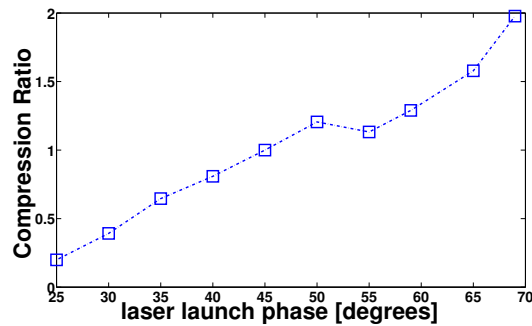


**FIGURE 4.** The beam image at X7 with the deflecting cavity OFF (top) and ON (bottom) revealing the twin pulses. The y-projection between the peak intensities will yield the distance in pixels between the pulses.

on the deflecting cavity strength was modest. During the experiment, we had to limit the deflection strength to a even lower value ( $\sim 1$  kW) because the distance between the pulses were in 10's of picoseconds while the individual pulses were around  $\sim 0.1 - 1$  ps. Such a low value of the deflection strength will not resolve the individual pulse structure but will be sufficient to resolved the temporal positions of the bunch centroid. The twin pulses are evident from the projections along y-axis (in the inset) in Fig. 3 and Fig. 4. The distance between the pulses do not increase as it is fixed by the birefringence of the crystal to first order under normal operating conditions. The increase in the strength of the deflecting cavity increases the resolution of ps/mm thus showing the increase in distance as a function of the cavity strength. Conversely, this technique could be used to calculate the resolution of the deflection mode cavity as a function of the cavity strength without having to resort to a scan for a given strength of the deflecting mode cavity.

### Effect of laser launch phase

In an ideal scenario, the laser is launched about 45 degree from the crest to maximize the energy gain. But in the case of the twin pulse because of the time separation, one of the pulse might also undergo ballistic bunching. Therefore, the distance between the twin electron pulses should vary as a function of the laser launch phase. The effect of laser launch phase on the compression ratio - the ratio of the separation between the twin pulses compared to the normal operating conditions ( $45^\circ$ ) - is plotted in Fig. 5. This agrees well with the previous results at A0[13].



**FIGURE 5.** The effect of the laser launch phase on the time separation between the pulses. The time separation at  $45^\circ$  is taken as the normalizing value for a comparison.

### CONCLUSION AND FUTURE WORK

In this work, we have shown the possibility of using femtosecond UV pulses with  $\alpha$ -BBO crystals to shape the longitudinal profile of a low-energy electron beam. We plan to use two more crystals to generate different shapes and

understand the dynamics of space charge. A remotely controllable rotatable stage is planned to prevent mis-alignment for different crystal settings.

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